UNLIMITED
UNCLASSIFIED

Canada

INVESTIGATION OF THE TORQUE DEGRADATION OBSERVED DURING QUALIFICATION TESTING OF CANADARM JOINT BRAKES

by

J.M. Trenouth, C.W. MacKenzie
National Aeronautical Establishment

AERONAUTICAL NOTE
NAE-AN-38
NRC NO. 26161

OTTAWA
JULY 1986

National Research Council Canada
Conseil national de recherches Canada

NATIONAL AERONAUTICAL ESTABLISHMENT

SCIENTIFIC AND TECHNICAL PUBLICATIONS

AERONAUTICAL REPORTS:

Aeronautical Reports (LR): Scientific and technical information pertaining to aeronautics considered important, complete, and a lasting contribution to existing knowledge.

Mechanical Engineering Reports (MS): Scientific and technical information pertaining to investigations outside aeronautics considered important, complete, and a lasting contribution to existing knowledge.

AERONAUTICAL NOTES (AN): Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

LABORATORY TECHNICAL REPORTS (LTR): Information receiving limited distribution because of preliminary data, security classification, proprietary, or other reasons.

Details on the availability of these publications may be obtained from:

Publications Section,
National Research Council Canada,
National Aeronautical Establishment,
Bldg. M-16, Room 204,
Montreal Road,
Ottawa, Ontario
K1A 0R6

ÉTABLISSEMENT AÉRONAUTIQUE NATIONAL

PUBLICATIONS SCIENTIFIQUES ET TECHNIQUES

RAPPORTS D'AÉRONAUTIQUE

Rapports d'aéronautique (LR): Informations scientifiques et techniques touchant l'aéronautique jugées importantes, complètes et durables en termes de contribution aux connaissances actuelles.

Rapports de génie mécanique (MS): Informations scientifiques et techniques sur la recherche externe à l'aéronautique jugées importantes, complètes et durables en termes de contribution aux connaissances actuelles.

CAHIERS D'AÉRONAUTIQUE (AN): Informations de moindre portée mais importantes en termes d'accroissement des connaissances.

RAPPORTS TECHNIQUES DE LABORATOIRE (LTR): Informations peu disséminées pour des raisons d'usage secret, de droit de propriété ou autres ou parce qu'elles constituent des données préliminaires.

Les publications ci-dessus peuvent être obtenues à l'adresse suivante:

Section des publications
Conseil national de recherches Canada
Établissement aéronautique national
Im. M-16, pièce 204
Chemin de Montréal
Ottawa (Ontario)
K1A 0R6

UNLIMITED
UNCLASSIFIED

INVESTIGATION OF THE TORQUE DEGRADATION OBSERVED DURING QUALIFICATION TESTING OF CANADARM JOINT BRAKES

ÉTUDE DE LA DÉGRADATION DU COUPLE DE PATINAGE EN COURS D'ESSAIS DE QUALIFICATION DES FREINS DES ARTICULATIONS DU CANADARM

by/par

J.M. Trenouth, C.W. MacKenzie

National Aeronautical Establishment

AERONAUTICAL NOTE
NAE-AN-38
NRC NO. 26161

OTTAWA
JULY 1986

D.L. Simpson, Acting Head/Chef intermédiaire
Structures and Materials Laboratory/
Laboratoire des structures et matériaux

W. Wallace
Acting Director/
Directeur Intérimaire

SUMMARY

During the development of the Canadarm, its various components had been subjected to a number of tests at both acceptance and qualification levels. One of these involved the measurement of the slip torque of the joint drive brakes while operating under space-simulated conditions of temperature and pressure. In the latter stages of qualification testing, instances in which brake units showed a temporary decrease in brake slip torque had been observed. In order to assist in determining the cause of this behaviour, and investigation of the phenomenon was undertaken in this laboratory. The testing prior to this investigation is briefly reviewed and the NAE test results are presented.

RÉSUMÉ

Les divers composants du Canadarm ait été soumis en cours de développement à des essais de réception et de qualification. L'un de ces essais a impliqué des mesures du couple de patinage des freins de l'entraînement des articulations sous des pressions et à des températures simulant l'environnement spatial. Au stade final des essais de qualification, des diminutions du couple de patinage des freins ont été observées dans quelques cas. Une étude de ce phénomène a été entreprise par ce laboratoire pour en expliquer les causes. On résume brièvement les essais ayant précédé cette étude et on rend compte des résultats des travaux de l'ÉAN.

CONTENTS

		Page
	SUMMARY	(iii)
	ILLUSTRATIONS	(iv)
1.0	INTRODUCTION	1
2.0	DFL TEST OBSERVATIONS	2
3.0	NAE INVESTIGATION	4
3.1	Brake Slip Torque Results	6
3.2	Module Component Temperatures	9
3.3	Test Chamber Pressure	10
3.4	Residual Gas Analysis	11
3.5	Friction Material Characterization	13
4.0	DISCUSSION OF RESULTS	17
5.0	CONCLUSIONS	20
6.0	ACKNOWLEDGEMENTS	21
7.0	REFERENCES	21

ILLUSTRATIONS

Figure		Page
1	RMS Motor Module	23
2	Motor Module Brake Unit	23
3	Slip Torque During DFL Test Cycles 8 and 9	24
4	Test Fixture with Motor	25
5	Slip Torque, Motor Speed and Chamber Pressure During Brake Slip Test	26
6	Slip Torque During NAE Tests A to 6B-7	27
7	Slip Torque During NAE Tests C1 to I3	28

ILLUSTRATIONS (Cont'd)

Figure		Page
8	Module Component Temperatures During NAE Test B1	29
9	Mass Spectrometer Analyses of Test Chamber Atmosphere (a) During and (b) After Brake Slip Test	29
10	Brake Pad Surface Cavity	30
11	Brake Pad Surface Grooving	31
12	Surface Profile of Armature Brake Pad	32
13	XES Spectrum from Armature Pad	33
14	TGA Curves for Virgin Friction Material (-) and Brake Pad Wear Debris (--) Under Vacuum	33

INVESTIGATION OF THE TORQUE DEGRADATION OBSERVED DURING QUALIFICATION TESTING OF CANADARM JOINT BRAKES

1.0 INTRODUCTION

The Canadarm or Remote Manipulator System (RMS) for the Space Shuttle resembles a human arm in that it consists of upper and lower arm booms, an end effector or hand, and shoulder, elbow and wrist joints. The latter components, which provide the articulated system with arm movement capabilities comparable to the human analogue, are driven through gear trains by individual drive motor systems referred to as joint motor modules (Figure 1). The primary components of each of these modules are a dc servo motor, an optical commutator, a tachometer, and an electromechanical, disk-brake assembly.

The disk brake in each motor module is used as a holding device to maintain joint rigidity, and may be used to arrest arm motion when required. The brake is a clutch-type, spring-loaded unit in which braking force is provided by the friction between a pair of dimensionally identical, annular-shaped, brake pads. The two opposing pads, which are adhesively-bonded to metal backing plates are compositionally similar, being made from a phenolic resin/asbestos composite. One of the friction pad-backing plate combinations, the shaft assembly or rotor (Figure 2), is an integral part of the motor module drive shaft, and is thus capable of rotation about the brake axis but is stationary with respect to axial translation. The other pad-plate assembly, the sliding armature, is fixed rotationally but capable of axial translation to effect brake pad engagement/disengagement. Designed for fail-safe operation, the brake is normally engaged - the opposing pads being held in contact by engagement springs bearing on the back face of the sliding armature. Brake release is effected by energizing the solenoid, which results in the withdrawal of the armature and disengagement of the pads.

One of the component tests in the development of the Canadarm involved the measurement of the slip torque of the disk brake under the low pressure and variable

temperature conditions experienced in space. The evaluations were carried out by Spar Aerospace Ltd., the prime industrial contractor in the development of the Canadarm, in a thermal-vacuum facility at the David Florida Laboratory (DFL) of the Department of Communications. This report describes an unusual slip torque behaviour that was observed during the DFL tests and presents the results from a subsequent NAE investigation of this phenomenon.

2.0 DFL TEST OBSERVATIONS

Near the completion of qualification thermal-vacuum testing of one of the brake units, an anomalous loss of brake slip torque was observed. The loss occurred during the seventh cycle of an eight cycle qualification thermal vacuum test of joint brake unit 207-1. In this cycle, slip tests were conducted at 10°C increments as the temperature was increased from ambient to a high temperature limit of 93°C and then, after reducing the temperature to ambient, at 10°C increments as the temperature was reduced to the low temperature limit of -36°C. All brake slip readings were normal during the heating phase. However, during the cooling stage, the torque values decreased with each successive test until, at the low temperature extreme, one of thirty-six slip torque readings was below specification (41 oz-in versus 50 oz-in minimum). The temperature was then raised to ambient and slip torque measurements taken; all thirty-six readings were below specification. However, after venting the chamber to atmosphere, all readings were again within the normal torque range of 68-72 oz-in.

Additional occurrences of slip torque degradation were observed with this brake during a subsequent investigation of the phenomenon at DFL. After the seventh thermal vacuum cycle of the qualification test, the test chamber was re-evacuated and the recovered brake was again tested during a thermal cycle. Initially, tests were conducted at 10°C intervals as the temperature was reduced to and held at -36°C. The brake exhibited a similar behaviour to that previously observed; the torque values progressively decreased until, at the low temperature extreme, values were again below the lower specification limit of 50 oz-in (Figure 3). After a 20 hour hold at -36°C the unit temperature was increased to the hot plateau. Measurements taken during this temperature transition showed a continued decrease in brake slip torque values until, at

the high temperature extreme, a value of only 10 oz-in was obtained. The slip torque increased only slightly in tests performed during the return of the unit to ambient temperature, but immediately increased to 76 oz-in upon releasing the vacuum.

The test chamber was then re-evacuated, but maintained at ambient temperature, while the brake torque was periodically measured. After obtaining acceptable values for fourteen hours, the torque decreased to 24 oz-in over a fifteen hour period. Subsequently, the torque increased to approximately 64 oz-in during a twenty hour interval, and then gradually increased to 70 oz-in over an additional forty-three hour period.

In a final set of tests in this series, the brake slip torque was measured at hourly intervals during a thermal cycle. The torque decreased slightly during cooling from ambient, reaching a value of 65 oz-in at -36°C. However the torque continued to decline as the temperature was increased to the high temperature plateau, at which point it was only 13 oz-in. Three subsequent tests, in which high speed spins (70 rad/s) of the disengaged rotor were performed before testing, resulted in only minor increases in the slip torque. However, acceptable values were again immediately obtained after venting the chamber to atmosphere.

After being dismantled, examined and cleaned, brake 207-1 was reassembled and tested at DFL along with two other joint brakes. Instances of slip torque loss were observed with each brake unit. In all cases, degradation of torque began at the minimum of a thermal cycle and continued as the temperature was subsequently increased. However, recovery of acceptable torque always occurred near the maximum of the next thermal cycle and all recoveries occurred while maintaining the units in vacuum.

Prior to the initial loss of acceptable brake slip torque, joint brake 207-1 had successfully completed forty-two slip tests during acceptance and qualification testing, and the brake pads had sustained almost 26,000 slipping revolutions. Because of this extensive slippage, it had been initially concluded that the brake's eventual failure to meet its slip torque requirement was probably due to an accumulation of brake pad wear debris. However, this conclusion was not supported by the observation that, after being refurbished, the brake continued to show instances of torque loss. These latter tests,

involving additional brake units, also showed that the behaviour was not a unique characteristic of 207-1.

Summarizing the results of the DFL tests, loss of brake slip torque was observed on several occasions with different joint brake units. Thermal cycling appeared to be a significant factor in initiating torque degradation. However the series of tests carried out under (constant) ambient temperature conditions showed that temperature transitions were apparently not essential for torque loss to occur. There was a definite correlation between immediate recovery of acceptable torque values and venting of the test chamber to atmosphere. However this correlation also has to be tempered by the observations of torque recovery that occurred while maintaining the brake units in vacuum.

This anomalous brake behaviour was not viewed as a problem for current Canadarm requirements because the extensive brake pad slippage that preceded torque degradation during the rigorous qualification tests was well in excess of Shuttle mission estimates. In addition, torque recovery was always effected by return of the brake unit to ambient (sea-level) pressure. There was concern, however, that the cause of the slip torque loss could not be identified, and it was recognized that the phenomenon could have more serious implications for extended applications of the manipulator arm in space. In order to assist in its resolution, an investigation of this brake slip behaviour was undertaken in this laboratory.

3.0 NAE INVESTIGATION

The objectives of the NAE investigation were to attempt to duplicate the DFL test results and, assuming that the torque degradation could be reproduced, to identify the cause of the anomaly. To this end a thermal-vacuum test facility was designed and constructed at NAE, and a brake slip torque test program was developed[1].

The NAE test facility was developed for the evaluation of RMS joint brake units under temperature and pressure conditions simulating space exposure. The facility provides for the thermal control of the brake unit in a vacuum chamber, and the computer-controlled drive and torque measurement of the brake by an externally-mounted

drive motor/torque sensor system. The test facility has four major components: a vacuum chamber with appropriate instrumentation including a mass spectrometer to identify any evolved gases, a test fixture, a temperature-control system, and a data acquisition and control system. The test fixture (Figure 4) consists of a support frame for the motor module, mounted on the vacuum side of one of the test chamber end plates, and a drive motor, tachometer, gear reducer, torque cell system mounted on the external side of the end plate. A low-friction, rotary-shaft, vacuum feedthrough in the chamber end plate provides the mechanical connection between the brake unit and this external system. The temperature of the test article is controlled by circulation of a heat-transfer fluid through a copper coil surrounding and in thermal contact with the unit. With this technique, the vacuum chamber walls remain virtually at ambient temperature during heating and cooling of the module and thus have little effect on the gas load and composition of the chamber atmosphere. The data acquisition and control system consists primarily of a dedicated computer, a signal acquisition and conditioning unit, a relay control unit, and various sensors for test chamber pressure, motor module component temperatures, brake rotational speed/direction and brake slip torque. A number of computer programs were developed to control the motor speed, brake activation and acquisition of data during the tests. Programs were also developed to test and troubleshoot various aspects of the test system. The main test control program enabled the system to: (a) guide the test operator by prompting for temperature and pressure changes, (b) control the brake solenoid, and the drive motor rotational speed and direction, and (c) read and record the temperatures at various module locations.

The test procedure that had been developed for this investigation was based on the program followed by Spar at DFL. In summary, brake slip tests were performed at ambient temperature in an inert atmosphere, at ambient temperature in a vacuum of 133 μPa (10^{-6} torr) or less, at temperature extremes of +93 and -36°C during five thermal cycles in vacuum, and in a sixth thermal cycle, at 10°C intervals as the unit temperature was increased from ambient to 93°C and then as the temperature was decreased from ambient to -36°C. Each brake slip test consisted of a free brake spin (pads disengaged) at 7 rad/s for one minute in each direction followed by engagement of the pads and measurement of the torque as the pads were slipped at either 7 or 10 rad/s (67 or 96 rpm) for a series of 10 second slips. A total of thirty-six 10 second slips were performed during

each test, in six groups of six, alternating between clockwise and counter clockwise slip direction and with a momentary disengagement of the brake pads between each group of six slips. In addition to these slip tests, free brake spins were performed at 30 minute intervals during the heating and cooling stages of the first five thermal vacuum cycles. Each of these spins consisted of disengaging the brake pads, and rotating the free brake disk at 10.5 rad/s for 30 seconds in each direction. The brake pads were always re-engaged upon completion of each of these spins.

3.1 Brake Slip Torque Results

The slip torque generated by the disk brake of the motor module was monitored during each test by recording the output from the torque sensor on a strip chart recorder (Figure 5). Also monitored were the pressure and composition of the chamber atmosphere, and the drive motor rotational speed and direction.

Values for the initial (breakaway or stiction) torque in each group of six slips, and values for the maximum, minimum and mean torque for each of the thirty-six brake slips in each test, grouped according to the direction of slip, i.e. 6 cw, 6 ccw, 6 cw, 6 ccw, 6 cw, 6 ccw, were read from the strip chart records. The average mean torque was determined for each group of six slips and plotted for each brake test along with the corresponding test temperature (Figure 6).

Brake slip torque values of approximately 65 oz-in were obtained during the initial ambient temperature tests in both argon (Test A) and vacuum (Tests B1 and B2), and the scatter of values for each test was small. These values, which were in the middle of the acceptable brake slip torque range (50-78 oz-in), indicated that operation of both the brake unit and the NAE test facility were satisfactory. The results also showed that the torque developed by the brake was independent of whether or not the test was conducted under atmospheric pressure (argon) or dynamic vacuum (13 μ Pa) conditions.

Closely grouped torque values were also obtained for each test during the first two thermal vacuum cycles and the values varied inversely with the test temperature. However, with subsequent testing, a progressive degradation in brake torque occurred and

the scatter of values for each test increased. Torque values below the lower specification limit were obtained in the fourth, fifth and sixth thermal cycles. Although low values were noted during both the high and low temperature halves of each cycle, it was apparent that the initiation of torque degradation occurred during testing at or near the low temperature limit. For the last thermal cycle, in which the tests were conducted at 10°C intervals and thus provided a more detailed view of brake behaviour with respect to temperature, significant loss of torque began during the third low temperature test at -7°C.

Recovery of brake slip torque was observed during the high temperature tests of these cycles, while maintaining the motor module in vacuum. The high temperature tests of the sixth cycle indicated that recovery of brake slip torque did not begin until tests were performed near the high temperature extreme, during the sixth test at 83°C. Although more pronounced in the sixth cycle, it was apparent that during these high temperature tests, the torque progressively increased within each test, whereas during the low temperature tests, the torque progressively decreased within each test.

During these last three cycles the torque at the end of a half cycle was the same as or very similar to the torque at the beginning of the next half cycle. This was considered to be significant since the test in each half of a thermal cycle was conducted on a separate, consecutive day after an intervening, overnight hold in vacuum at ambient temperature. There was a similar ambient temperature hold between the fourth and fifth thermal cycles and a four day hold at ambient temperature between the fifth and sixth thermal cycles. Clearly, neither the return of the brake to ambient temperature at the mid-point or at the end of a thermal cycle, nor the subsequent temperature change either to +93 or -36°C after an extended hold at ambient temperature had any significant effect on the brake slip torque; major changes in torque appeared to occur only during testing.

Because of frictional heating during brake pad slipping, it was anticipated that the temperature of the brake pads, particularly their surfaces, would increase during a slip test and possible affect the brake torque. However, the similarity in torque values at the end and beginning of successive cycles indicated that the torque was not affected by any increase in brake pad temperature during a test. The observation that either torque

increase or torque decrease could occur during a test also showed that any friction-induced temperature rise at the brake pad interface during these tests had no effect on the brake slip torque.

At the completion of the sixth thermal cycle, the brake was returned to ambient temperature and maintained in a dynamic vacuum (13μPa) for two days. Tests performed at the end of this period showed that no significant change had occurred (Figure 7); the brake unit had remained in its low torque mode during the temperature transition and two day hold at ambient temperature in vacuum, as well as during the subsequent slip tests at ambient temperature. Over a further period of eight days, during which time testing was conducted intermittently, the brake remained in this low torque mode. Clearly, under these thermal vacuum conditions, this mode was a stable configuration in which the brake unit could remain indefinitely, even with periodic slip testing. Such behaviour does not support any kinetic mechanism for the torque loss such as the more familiar, temperature-induced fade and recovery that may be observed with vehicular brakes.

The brake unit was then returned to atmospheric pressure by slowly back-filling the test chamber with argon. Measurements taken during the pressurization showed a rapid recovery of acceptable brake slip torque; from a low value of 14 oz-in mid-way through the first set of six brake slips, the torque rapidly increased, reaching 53 oz-in by the end of the second set of slips. After two subsequent sets of brake slips, the torque had stabilized at approximately 62 oz-in. This result is in good agreement with the DFL test results in which brake units exhibited immediate recovery of acceptable slip torque upon pressurization of the test chamber with either air or nitrogen.

The brake torque remained within specification during subsequent tests in vacuum, indicating that, by exposure to atmospheric pressure, the cause of the low brake slip torque was removed and there was no tendency for the brake to revert, at least immediately, to its low torque configuration upon re-exposure to vacuum conditions.

A repeat of the sixth test cycle in which torque measurements were made at 10°C intervals during heating and cooling of the module showed no major changes until the fifth test of the cooling phase (Figure 7). During this test, at -26°C, the torque rapidly

decreased with each set of brake slips. The torque continued to decline during two subsequent tests at -36°C, the last test being done after a one hour thermal stabilization period, at which point the slip torque was 22 oz-in. This loss of torque indicated that conducting a complete, six cycle, thermal vacuum test was not essential for slip torque degradation. It was also apparent that the phenomenon responsible for the loss of torque had not been permanently deactivated by the previous exposure of the brake to atmospheric pressure. An attempt to initiate a further torque degradation of the recovered brake by repeating only the low temperature half of this cycle was unsuccessful, suggesting that tests at or near the high temperature extreme were necessary in order to induce torque loss during subsequent low temperature tests.

3.2 Module Component Temperatures

The temperatures indicated by thermocouples at six locations on the motor module were determined every two seconds by computer during a slip test. For each group of slips (cw or ccw), the maximum and minimum temperatures at each location were tabulated. At the completion of each brake test, all of the temperature readings, which had been stored on disk, were recalled and plotted.

The locations of the thermocouples on the module were identical to those employed during the DFL tests. These sites had been initially selected in order to monitor the temperatures of the active module components. However, in the current NAE tests, all of the module components, with the exception of the brake unit, were inactive; the conversion of the rotational energy of the brake disk to frictional heat during braking was the only source of heat in the module. It was anticipated that this heat would be absorbed by the friction pads and subsequently dissipated by conversion to chemical energy (thermal degradation of the friction pads and/or evaporation of low-boiling constituents) and by transfer to the surroundings via the usual heat transfer modes. As a result of the latter processes, it was expected that during testing the brake housing would show the largest increase in temperature and more distant module locations would show smaller changes or possibly remain isothermal. The temperature plots of the module component temperatures during the brake slip tests confirmed this anticipated behaviour (Figure 8). Thermocouple No. 2, which monitored the temperature of the brake housing, showed the

greatest increase during testing, while the remaining thermocouples showed no significant changes. In all cases, however, the changes in temperature of the brake housing were relatively small. The maximum temperature increase was approximately 1°C or less for all slip tests done in vacuum, and approximately 2°C for slip tests done at atmospheric pressure. It was concluded that these relatively small changes in temperature were due to the low heat conductivity of the organic-based friction pad material which prevented a rapid flow of heat from the surfaces of the brake pads to the other module components. Instead, a mechanism was favoured in which a steep thermal gradient was created in the brake pads and much of the heat energy at the pads' interface was converted into chemical energy either by outgassing from or thermal degradation of the brake material.

3.3 Test Chamber Pressure

The pressure of the vacuum chamber was observed to fluctuate with the operation of the brake unit during slip testing. Chart recordings of these pressure fluctuations (see Figure 5) indicated that, during a test, the chamber pressure was a function of the brake slip speed and resulting torque beginning with a pressure rise as the slip speed and torque increased, a relatively steady or slightly increasing pressure as the slip torque remained constant, and then a pressure drop as the torque decreased. It was apparent that the pressure fluctuations were due to the evolution of gases during brake slippage as a result of thermal desorption (degassing) and/or thermal degradation (pyrolysis) of the components of the composite brake material.

A significant difference in magnitude of the pressure fluctuations was apparent for the high and low temperature tests of each thermal cycle. This difference which was larger than could be accounted for by simple thermal expansion indicated that a greater amount of gas was produced during brake slip at the higher temperature. Such behaviour would be expected for any thermally-activated process such as gaseous desorption from or pyrolysis of the friction material.

During the first half of the sixth thermal cycle, in which brake tests were performed at 10°C increments as the module temperature was increased from ambient to 93°C, the brake slip torque decreased to approximately 25 oz-in and then recovered to 54 oz-in.

There was a direct correlation between this loss and recovery of torque, and the magnitude of the pressure fluctuations. Similar behaviour was also evident for the torque losses that occurred during the second half of the sixth cycle and during the subsequent repeat of that cycle. This correlation between the pressure and slip torque (i.e. friction) confirmed that the observed fluctuations were due to gases evolved as a result of frictional heating of the brake pads.

A brake test done at a slip speed of 1 rad/s resulted in a similar slip torque to that obtained during the usual tests at 7 and 10 rad/s. However the pressure fluctuations during the 1 rad/s slip test were an order of magnitude smaller. It was evident that, while the slower slip speed had no effect on the brake torque, it did result in a substantially reduced pressure fluctuation due to the reduction in the rate of work input to the brake ($\propto$velocity^2), and hence in the frictional heat available for the thermally-induced evolution of gases.

3.4 Residual Gas Analysis

A mass spectrometer analysis of the residual atmosphere in the test chamber was performed during each of the low-pressure, brake slip tests. A mass spectrum was also obtained before and/or after each of these tests. From a comparison of these spectra (Figure 9), any change in the composition of the test chamber atmosphere due to brake operation (i.e. brake slip) could be determined. By reference to mass spectra tables, a qualitative estimate could be made of the composition of the gaseous atmosphere arising from each brake slip test.

For most of the analyses, the spectrometer scanned the mass spectrum between 0 and 60 atomic mass units (amu) in 100 seconds. During this time interval, approximately nine 10 second brake slips occurred. As a result of the cyclic nature of the slip testing and hence of the gas evolution, the possibility existed that in this continuously-evacuated system the analyzer would detect less than the maximum amount of a particular ion if, during the mass scan, the analysis for that ion's mass number occurred during the acceleration or deceleration of a brake slip. However, since the identification of parent molecules, with the exception of H_2, was based on the presence of two or more specific

ions, the analyses were considered to be representative of the gas composition existing in the test chamber, allowance being made for possible errors in the concentration of hydrogen.

A comparison of the spectra obtained during and after the second ambient temperature test in vacuum showed that there had been increases in the concentrations of species with mass numbers 2, 12, 15, 16, 17, 18, 28 and 44 during the brake slip. The peak heights for the ions with mass numbers 17 and 18 were in the 1:4 ratio characteristic of the water vapour cracking pattern. Consequently, the increased height for this pair of peaks was attributed to an increased concentration of water vapour during the friction test. Such an increase could be expected, particularly for the first tests in vacuum, as a result of thermal desorption of water vapour from the friction pads. The remaining peaks in the spectra, for which relative increases in height were apparent, were assigned by reference to mass spectra tables to H_2, CH_4, CO and CO_2. Thus, the residual atmosphere in the test chamber had been enriched in water vapour, hydrogen, methane and the oxides of carbon during the brake test.

As a result of outgassing, the spectrum for the (succeeding) high temperature test of the first thermal cycle was slightly more complex and was dominated by water vapour peaks. However, by using the spectrum of the chamber atmosphere taken immediately after the test as the baseline, it was apparent that the major changes due to brake slip were in the peak heights at 12, 15, 16, 28 and 44 amu. The parent compounds identified for these peaks were CH_4, CO and CO_2. Although the test spectrum indicated that a relatively high concentration of water vapour was present in the chamber atmosphere during this test, the similarity of the water vapour peak heights with those in the post-test, baseline spectrum indicated that it was not a major component of the gas evolved during this brake slip.

In all subsequent tests, including those in which the brake was in its low torque mode, the primary gases in the residual atmosphere of the test chamber that could be attributed to evolution during brake slip were the organic degradation products H_2, CH_4, CO and CO_2. Even when brake tests were done under static vacuum conditions and the evolved gases were allowed to accumulate in the chamber, no additional species were

detected. During these latter tests, it was apparent that as the concentrations of H_2, CH_4, CO and CO_2 increased by accumulation, the concentration of water vapour (17 and 18 amu peaks) became relatively minor, confirming that no significant amount of water was evolved from the rubbing pads after the initial outgassing.

Jackson and Conley investigated the degradation of phenol-formaldehyde polycondensates at temperatures up to 1000°C[2]. They found that the main products of pyrolysis of the phenolic resins were CO_2 and CO. Water, paraformaldehyde, methane and aromatic products were also formed. The authors concluded that the primary degradation route, regardless of whether the resin was exposed to elevated temperatures in air, argon or nitrogen, was oxidation, with the resin itself acting as a source of oxygen. At the higher temperatures, thermal degradation products were observed in addition to those formed by oxidation. However, throughout the temperature region studied, the oxidative degradation, as indicated by the formation of CO_2 and CO, was always more pronounced. A subsequent investigation of the degradation of phenolic resins by mass spectrometric thermal analysis[3] confirmed the thermal oxidative mechanism proposed by Conley and co-workers although, in this latter study, H_2 was also detected in the degradation products. On the basis of these investigations on phenolic resins, it was concluded that the gases evolved during brake slip came from the oxidative degradation of the organic component of the composite brake pads. It was also concluded on the basis of these studies and, in particular, on the basis of the appearance temperatures for the various products of pyrolysis and their variation with pyrolysis temperature, that instantaneous temperatures in the range of 500°C and possibly higher could have occurred at the interface of the brake pads during brake slip.

3.5 Friction Material Characterization

At the completion of the NAE testing, brake unit 207-1 was disassembled for examination. It was estimated that, at this stage, the brake pads had experienced over 200,000 slipping revolutions. Most of these slips had been carried out during tests in vacuum, and all tests had been performed at temperatures between -36 and +93°C.

Accumulations of a tan-coloured, wear debris were observed on both annular brake pad assemblies, primarily adjacent to the friction pads. The debris was adherent to the surfaces of the brake components, but could be dislodged by light brushing. Scanning electron microscope (SEM) examination showed that the debris was a finely-divided powder with no evident carryover of asbestos fibrils from the brake pads.

The rubbing surface of each of the annular brake pads had a glazed, mottled appearance. Microscopic examination indicated that this mottling was due to smearing of the light-brown wear debris in patches on the contacting surfaces, and to accumulation of the debris in cavities in the surfaces of the brake pads. The cavities appeared to have developed where particulate inclusions or asbestos fibres intersecting the surface had been pulled out or decomposed during slip torque testing. Some of these cavities were relatively large, extending across a millimeter or more of the 6 mm wide brake pad surface (Figure 10).

Pronounced concentric grooves or furrows on both friction pads (Figure 11) were apparently caused by protrusions from the opposing pad surface. Resinographic examination of the virgin friction material showed that, in addition to bundles of asbestos fibres in the resin matrix, there were numerous particulate inclusions in the composite. Some of these were identified as graphite particles that had been added to the composite as a friction modifier. Others were considered to be mineral impurities associated with the asbestos[4-6]. It was assumed that the exposure of these latter inclusions at the pad surfaces by preferential degradation and abrasive wear of the phenolic matrix could have been responsible for these surface irregularities[7].

A surface profile graph from the armature brake pad surface is shown in Figure 12. Because the surface topography is due to concentric grooves rather than a random distribution of asperities and cavities, traces across the pad surface at various locations were very similar. In addition to the general scoring, the profile showed that a concave contour had developed across the armature pad surface, with two major depressions in the central concave region of the surface, as indicated by the dashed line in Figure 12. This characteristic of the profile indicated that, during the slip torque testing, the degree of wear was greatest in the central regions of the pad surface, while areas near the inner and outer edges experienced less material loss. This wear pattern was unexpected on the basis

of the dynamics of the slipping brake pads. Since the relative motion of the outer edge of the armature brake pad is greater than the inner edge, an increasing rate of wear, radially across the pad from the inner to the outer edge, would have been expected. The differential rate of working would also result in a higher temperature and an increase in wear at the outer edge of the brake pad[8].

In contrast to strong x-ray diffraction (XRD) patterns for chrysotile asbestos that had been obtained from both filings and a bulk sample of the virgin friction material, attempts to obtain an XRD pattern from the brake pad wear debris were unsuccessful, suggesting either too fine a particle size or non-crystalline material. Since SEM examination showed that the particles of wear debris appeared to be within the optimum range of crystal size for XRD[9], it was concluded that the crystalline asbestos of the virgin friction material had been reduced to an amorphous form at the brake pads' interface during brake slip. In the temperature range of 650-780°C, chrysotile is known to be thermally decomposed to an amorphous form with no recognizable crystallinity[10]. Above this temperature range forsterite (Mg_2SiO_4) may form from the decomposition products, while below approximately 650°C chrysotile is not thermally decomposed[5]. While the rubbing action of the slipping pads may have encouraged this thermal degradation reaction to occur at slightly lower temperatures, the inability to obtain an XRD pattern from the wear debris may be an additional indication that relatively high, transient temperatures were occurring at the braking interface during brake slip.

Spectra obtained by x-ray energy spectrometry (XES) for samples from the armature and shaft assembly pads of the tested brake and for a sample of the brake pad wear debris were similar to each other and similar to that from the virgin friction material. All of the spectra showed major peaks for magnesium and silicon, the identifiable elements in the chrysotile asbestos constituent ($Mg_3(Si_2O_5)(OH)_4$) of the friction material (Figure 13). Lesser peaks for calcium and iron were also present in all of the spectra. These were attributed to either ionic substitution of these elements in the asbestos[11] or to impurities commonly associated with this mineral, such as magnetite, Fe_3O_4[4]. The general similarity between the spectrum for the wear debris and that for the virgin material indicated that the chrysotile asbestos component had been worn from the brake pads and was present in some chemical form in the debris. However, on the basis of the SEM examination and the x-ray diffraction analysis, it was apparent that the

chrysotile was not present in the wear debris in its original fibrous, crystalline form, further supporting the thermal degradation hypothesis.

Weight-loss data from the thermogravimetric analysis (TGA) of samples of filed virgin material and brake pad wear debris from a brake simulator are plotted in Figure 14. It was apparent that, after heating to and stabilizing at 120°C (16h), the onset of measurable weight loss occurred at approximately 200°C. Initially the rate was faster and the weight loss was greater for the wear debris, suggesting that there was a greater amount of more volatile components in the wear debris than in the virgin material. With continued heating, the virgin material degraded in two main stages, around 400 and 550°C, followed by a lesser stage above 800°C. The wear debris did not have the low temperature degradation stages as clearly defined, the weight loss occurring in more of a continuous step. At approximately 550°C the weight loss curves for the two samples crossed over as the rate of weight loss for the virgin material exceeded that for the wear debris. As might be expected for these two materials, at the end of the heating period, the total weight loss was greatest for the virgin material.

These observations are consistent with a mechanism of thermal degradation of the asbestos-polymer composite during brake slip to produce a wear debris containing lower molecular weight oligomers of the original polymer. Such species would vapourize at lower temperatures during subsequent thermal analysis, giving rise to the observed greater rate and degree of weight loss between 200 and 400°C for the wear debris. Similarly the cross-over of the weight-loss curves at about 550°C indicated that, as a result of thermal degradation during brake slip, the wear debris contained less of the more heat resistant, higher molecular weight species than the virgin phenolic resin composite.

In a further test, samples of the filed virgin material were preconditioned at 150°C and 200°C instead of at 120°C in an attempt to induce some thermal degradation. However the overall degradation process above 240°C was not influenced by the higher preconditioning temperatures. The TGA curves for samples preconditioned at these three temperatures were all similar to each other, and different from the TGA curve for the wear debris. Clearly, transient temperatures at the brake pads' interface during formation of the wear debris in the brake simulator were in excess of 200°C and support the contention that relatively high momentary temperatures had occurred at the brake pads' interface during the DFL and NAE tests.

4.0 DISCUSSION OF RESULTS

Instances of brake slip torque values below specification were observed during testing of RMS joint brake 207-1 in the NAE test facility. These results are in agreement with the original DFL test results and indicate that the loss of brake slip torque is a real and repeatable phenomenon. It was also evident from these combined results that the loss of torque is associated with the brake unit and not with: (a) any other component of the motor module, (b) the Motor Module Test Set used by Spar at DFL, (c) the method of torque measurement which differed for the DFL and NAE tests, or (d) environmental interference from a particular test facility.

The losses of brake slip torque, which always occurred relatively rapidly, appeared to be related to the process of brake slippage. All torque degradations occurred during brake slip testing; none occurred between tests. Similarly, all recoveries occurred during testing; none occurred between tests. Clearly some process or processes occurred during brake slippage to lead on the one hand to loss of torque and on the other hand to gain of torque. Furthermore, the loss of torque was not a transient phenomenon - the brake unit could remain in its low torque configuration for several days under constant thermal vacuum conditions even with continued brake slip testing. Similarly, a recovered brake had a stable configuration and showed no tendency to revert to its low torque mode upon re-exposure to reduced pressure.

Thermal cycling appeared to be a contributing factor to loss of brake torque; degradation commencing during the initial thermal cycles, and loss and recovery of torque correlating with testing at or near the low and high temperature extremes respectively. However the thermal transitions alone did not effect a significant change, the torque at the end of a test being similar to that at the beginning of the next test after a temperature transition consisting of an intermediate transition to ambient temperature, an overnight or longer hold at ambient and a subsequent change to that of the next test.

Insufficient testing has been done at atmospheric pressure for any conclusions to be made regarding the effect of vacuum on the behaviour of the motor module brake. However, for a brake in a low-torque configuration, the NAE and DFL tests showed that immediate recovery of acceptable torque always occurred when the unit was returned to

atmospheric pressure by back-filling the test chamber either with argon (NAE) or with air or nitrogen (DFL).

Evolution of significant quantities of gas was observed during brake slip testing. The gas was identified as a mixture primarily of CO_2, CO, CH_4 and H_2. Thermal degradation of the organic (phenolic) component of the friction disks as a result of friction-generated heat was identified as the source of these gases. The relative amounts of CO_2, CO and H_2 were observed to vary with the brake test temperature. However no correlation between the nature or quantities of the evolved gas and the loss of brake slip torque was apparent.

Only small increases in the temperature of the brake housing were noted during the brake slip torque tests. However, the composition of the evolved gas, and the XRD and XES analyses of the brake pad wear debris have indicated that transient temperatures in the range of 500 to 650°C may have occurred at the brake pads' interface. The cross-over temperature of 550°C for the TGA curves for virgin friction material filings and brake pad wear debris from a brake simulator appeared to confirm the possibility of these relatively high transient temperatures during slip torque testing. A combination of gaseous evolution due to pyrolysis and subsequent abrasion of the resulting carbonaceous surface layer could explain the absence of any significant heat affected layers on the surfaces of the brake pads.

No significant anomalies were apparent upon examination of the dismantled RMS brake; the condition of the unit was similar to that observed in its previous stripdown by Spar. The DFL and NAE tests have indicated that the low torque configuration of the brake unit is not permanent, the phenomenon disappearing upon exposure of the brake to atmospheric pressure. Consequently any characteristic related to this failure mode probably would no longer be evident upon examination of the brake under atmospheric conditions.

Both brake disks showed pronounced annular grooving of the pad surfaces. In addition to this general surface scoring, the armature brake pad was found to have a concave cross-sectional contour indicating that pad wear was greatest in the central region of the annular-shaped pad. This surface contour was unexpected; on the basis of

the relative motion of the slipping brake pads, increasing wear from the inner edge of the annular pad outward would be predicted.

Brake pad wear debris was smeared in patches on the pad surfaces and distributed throughout the interior of the brake, with particular accumulations on the rotor and armature plates adjacent to the friction pads. The amount of debris was less than expected on the basis of some reported brake slip tests, but did correlate with the observed low degree of pad wear. Optical and SEM examinations of the debris showed it to be a finely divided powder with no evidence of the asbestos fibrils that are present in the parent friction material. However, by XES analysis, the debris was found to have the same asbestos-related, chemical composition as the virgin friction material.

Although the cause of the loss of brake slip torque was not identified during this investigation, the characteristics of the loss and recovery of torque suggested that electrostatic charging of the rubbing brake pads may be a contributing factor. Triboelectrification, whether it be due to movement of electrons or ions, or to transfer of electrically charged material, can occur by contact and/or rubbing of two dissimilar materials, or by asymmetrical rubbing of similar materials[12]. Charge transfer can occur even with symmetrical rubbing of two similar objects if any inhomogeneity, anisotropy or difference in strain, temperature, etc. is present. In the motor module brake unit, symmetrical rubbing of two annular brake pads with the same composition occurs. However, the inhomogeneity of the friction material, being a composite of phenolic resin, asbestos fibres and particulate inclusions may be sufficient to lead to the development of static electrification. In addition, the high volume resistivity (10^{14} ohm-cm) determined for this material, indicates that there would be little charge dissipation through the pads to the metallic backing plates of the brake unit, thus encouraging the build-up of electrostatic charge on the pads' surfaces.

A number of observations made during studies of triboelectrification appear to support the hypothesis that electrostatic charges could develop on the brake pads during slip and may be responsible for the observed losses of brake slip torque. Some of these are that the quantity of static charge can increase with the length of rub or number of revolutions[13,14], the polarity and magnitude of the charge can vary with temperature within the temperature range employed in the brake slip tests[14,15] areas of charge of

opposite polarity can co-exist in close proximity on the same insulating surface[16], and charge developed in vacuum can be dissipated by pressurization[14]. Further experimentation is being undertaken to determine whether or not stable electrostatic charges can develop on the surfaces of the brake pads during brake slip. It will also be necessary to determine whether such charges could result in the loss of torque due to accumulation of wear debris on the charged surfaces of the brake pads or to reduction in brake pad contact as a result of either pad repulsion or charge interaction with the brake solenoid coil.

5.0 CONCLUSIONS

1. Loss of brake slip torque which may occur during slipping of RMS joint brake units while thermal cycling in vacuum is a real and repeatable phenomenon.

2. The low torque mode that may be induced in RMS brake units is a stable configuration unlike the more familiar, temperature-related, transient fades of vehicular brakes.

3. Immediate recovery from the low torque configuration may be effected by exposure of the brake unit to atmospheric pressure.

4. Transient temperatures in the range of 500-650°C may occur at the brake pads' interface during slip torque testing.

5. Thermal degradation of the composite brake pads occurs at their interface during brake slippage.

6. Wear debris is produced as an adherent film-like constituent which possibly exerts a surface lubricating effect at the high transient temperatures suggested in (4) above.

7. Electrostatic charge may accumulate on the surfaces of the brake pads and either exert a repulsive effect between the pads, or be sufficient to cause the fine wear debris (dust) to be retained as lubricating particles at the interface.

6.0 ACKNOWLEDGMENTS

The assistance and cooperation of P.A. Adams, R.V. Dainty, P.H. Floyd and D.D. Morphy of the NAE Structures and Materials Laboratory are gratefully acknowledged.

We are indebted to Dr. M. Day of the NRC Chemistry Division for the TGA studies, and to Spar Aerospace Ltd. for permission to use the initial test information obtained at DFL.

7.0 REFERENCES

1. Trenouth, J.M. and MacKenzie, C.W. - Development of a Test Procedure and Facility for the Investigation of a Canadarm Joint Brake Anomaly, submitted for publication to the Canadian Aeronautics and Space Journal.

2. Jackson, W.M. and Conley, R.T. - High Temperature Oxidative Degradation of Phenol-Formaldehyde Polycondensates, Journal of Applied Polymer Science, Vol. 8, pp. 2163-2193, 1964.

3. Shulman, G.P., and Lochte, H.W. - Thermal Degradation of Polymers. II. Mass Spectrometric Thermal Analysis of Phenol-Formaldehyde Polycondensates, Journal of Applied Polymer Science, Vol. 10, pp. 619-635, 1966.

4. Badollet, M.S., and Ximenez, M.R. - The Role of Asbestos in Plastics, The Canadian Mining and Metallurgical Bulletin, Vol. 49, pp. 485-490, July 1956.

5. Jacko, M.G., Spurgeon, W.M., Rusnak, R.M., and Catalano, S.B. - Thermal Stability and Fade Characteristics of Friction Materials, SAE 680417, May 1968.

6. Badollet, M.S. - Asbestos, A Mineral of Unparalleled Properties, Canadian Mining and Metallurgical Bulletin, Vol. XLIV, pp. 237-246, April 1951.

7. Rakowski, W.A. - The Surface Layer of Friction Plastics, Wear, Vol. 65, pp. 21-27, 1980.

8. Newcomb, T.P., and Spurr, R.T. - Braking of Road Vehicles, Chapman and Hall Limited, London, 1966.

9. Brown, C.J. - The Intensity of the X-Ray Beam Diffracted from a Polycrystalline Aggregate, Chapter 16, X-Ray Diffraction by Polycrystalline Materials, H.S. Peiser et al (eds.), The Institute of Physics, 1955.

10. Rowson, D.M. - The Chrysotile Content of Wear Debris of Brake Linings, Wear, Vol. 47, pp. 315-332, 1978.

11. Callinan, T.D. - Fibre Materials, Chapter 3, Modern Materials, Advances in Development and Applications, Vol. 1, H.H. Hausner, Academic Press, 1958.

12. Harper, W.R. - Contact and Frictional Electrification, Clarendon Press, Oxford, 1967.

13. Montgomery, D.J. - Static Electrification of Solids, Solid State Physics, Advances in Research and Applications, Vol. 9, pp. 139-197, 1959.

14. O'Neill, B.C., and Foord, T.R. - Contact and Tribo Charging of Polymer Surfaces, 4th Conference on Static Electrification, London, England, 5-8 May, 1975, The Institute of Physics Conference Series No. 27, pp. 104-114, 1975.

15. Freund, T. - Tribo-Electricity, Advances in Colloid and Interface Science, Vol. 11, pp. 43-66, 1979.

16. Baum, E.A., and Lewis, T.J. - Controlled Charging of Insulator Surfaces, 4th Conference on Static Electrification, London, England, 5-8 May, 1975, The Institute of Physics Conference Series No. 27, pp. 130-140, 1975.

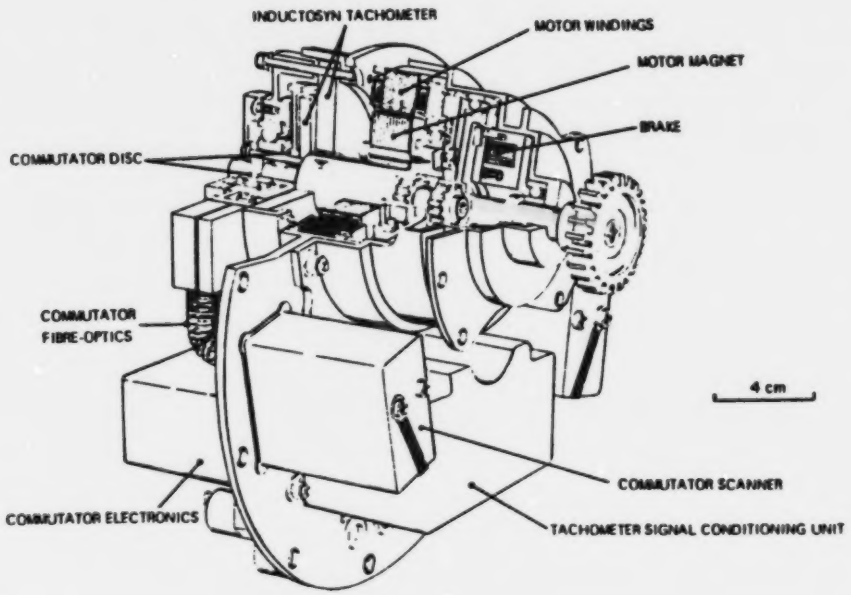


FIG. 1: RMS MOTOR MODULE

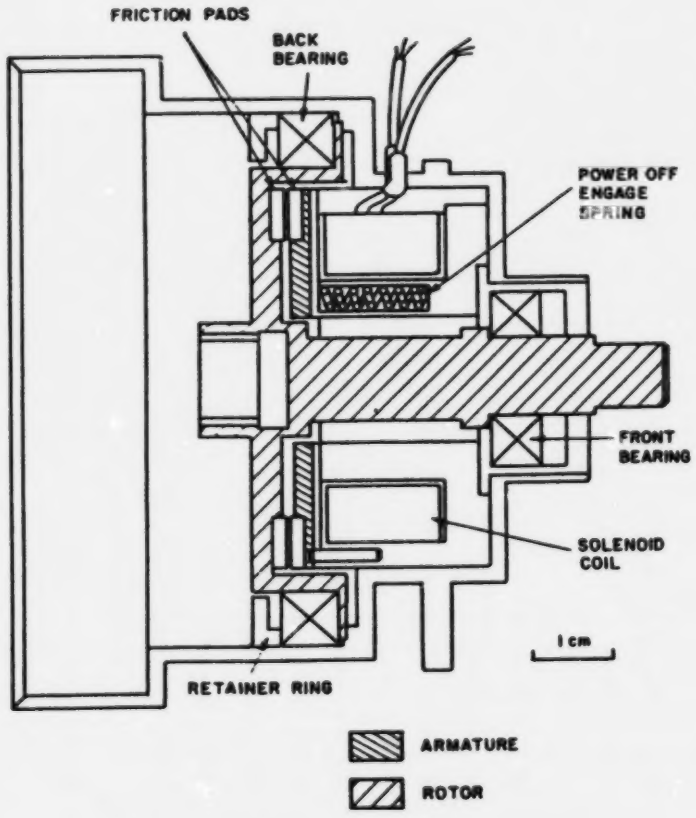


FIG. 2: MOTOR MODULE BRAKE UNIT

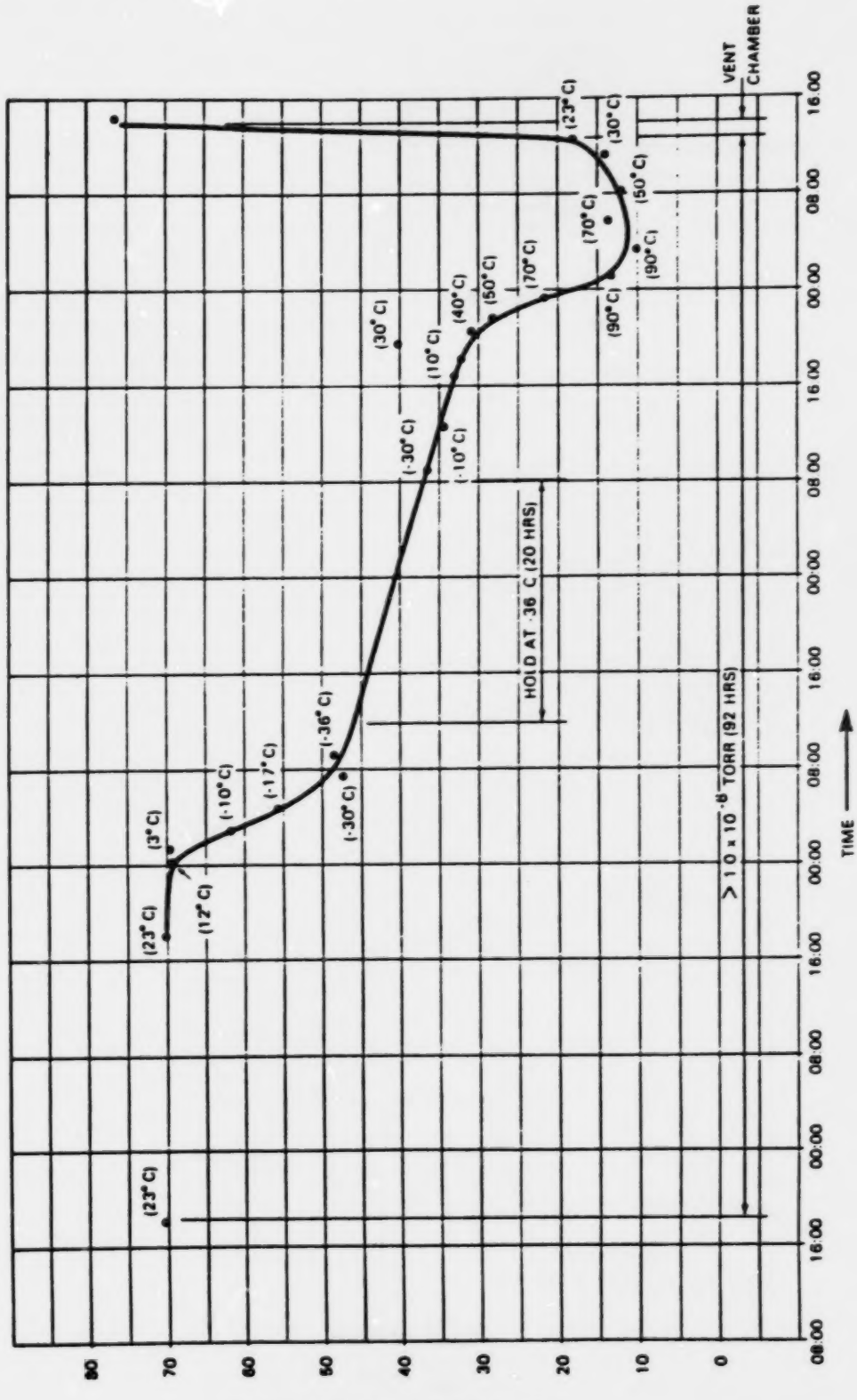


FIG. 3: SLIP TORQUE DURING DFL TEST CYCLES 8 AND 9

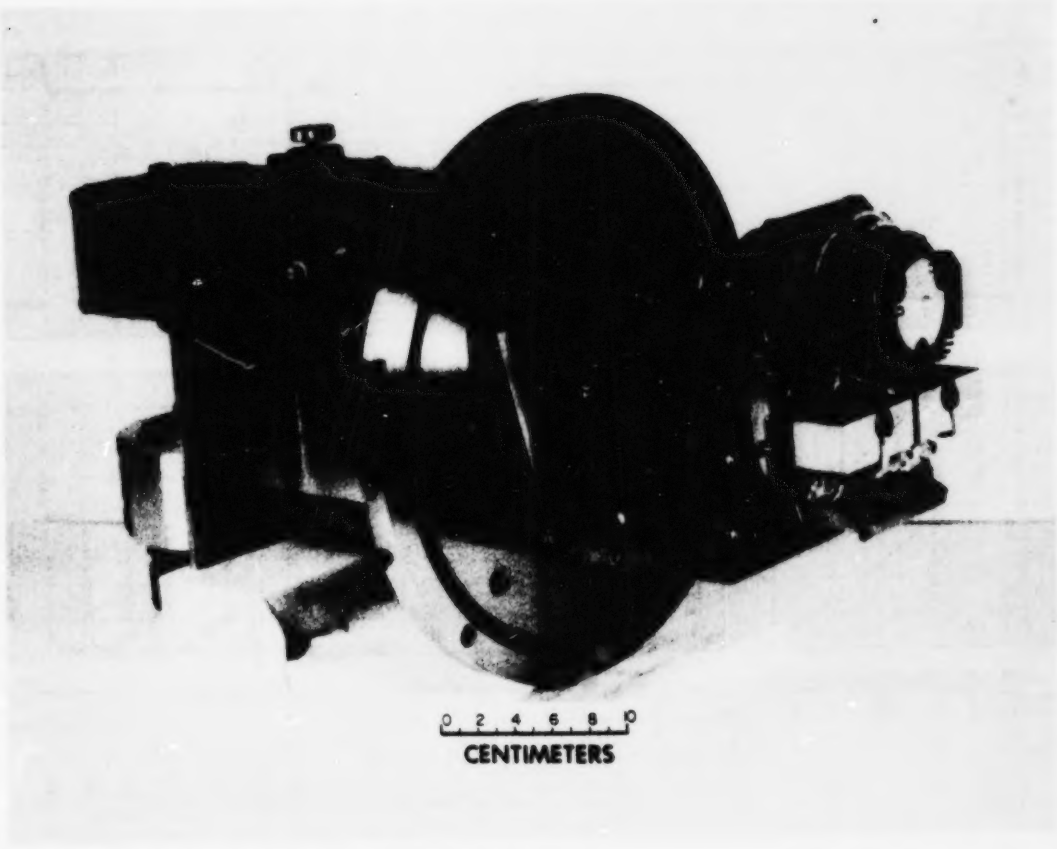


FIG. 4: TEST FIXTURE WITH MOTOR MODULE

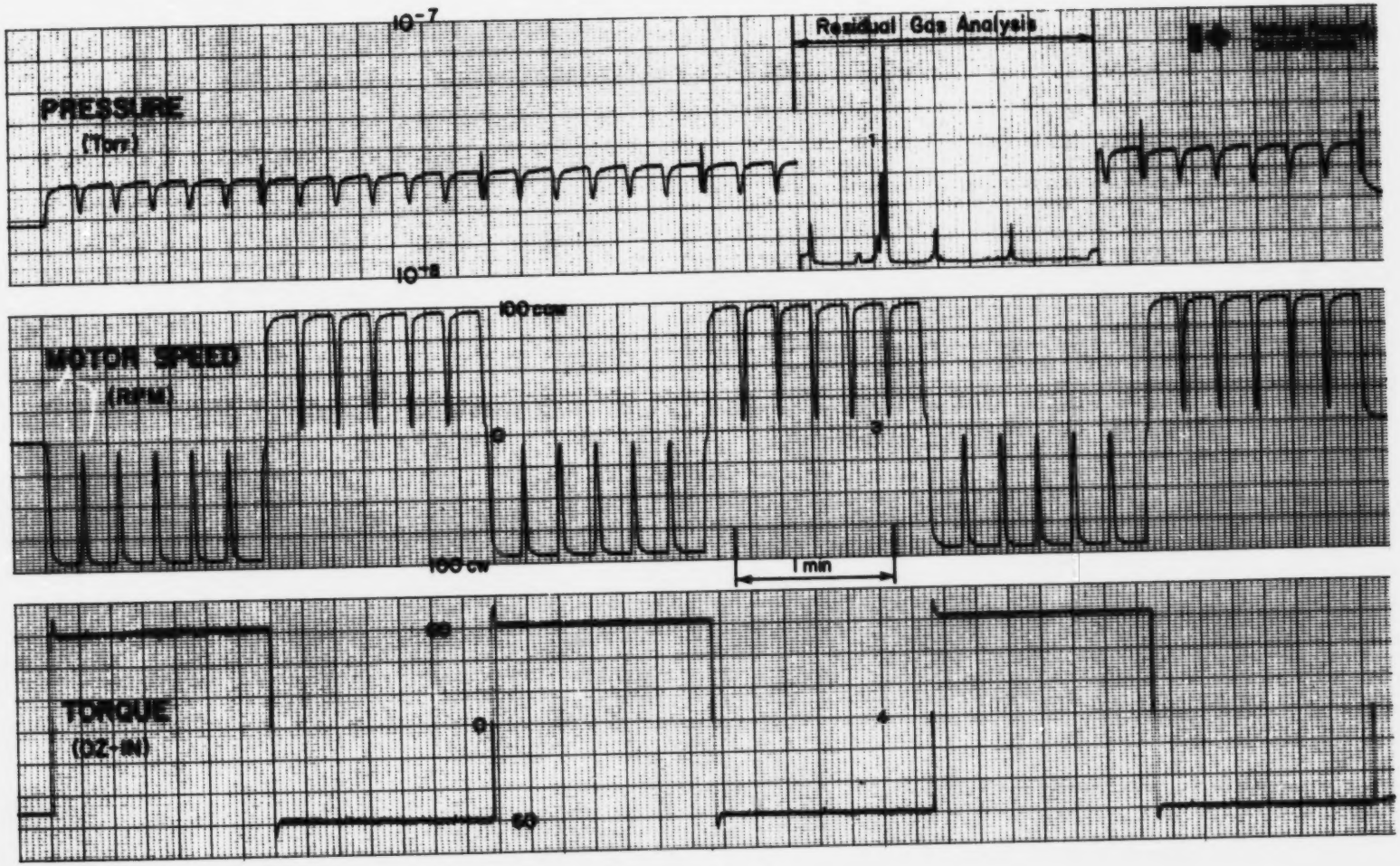


FIG. 5: SLIP TORQUE, MOTOR SPEED AND CHAMBER PRESSURE DURING BRAKE SLIP TEST

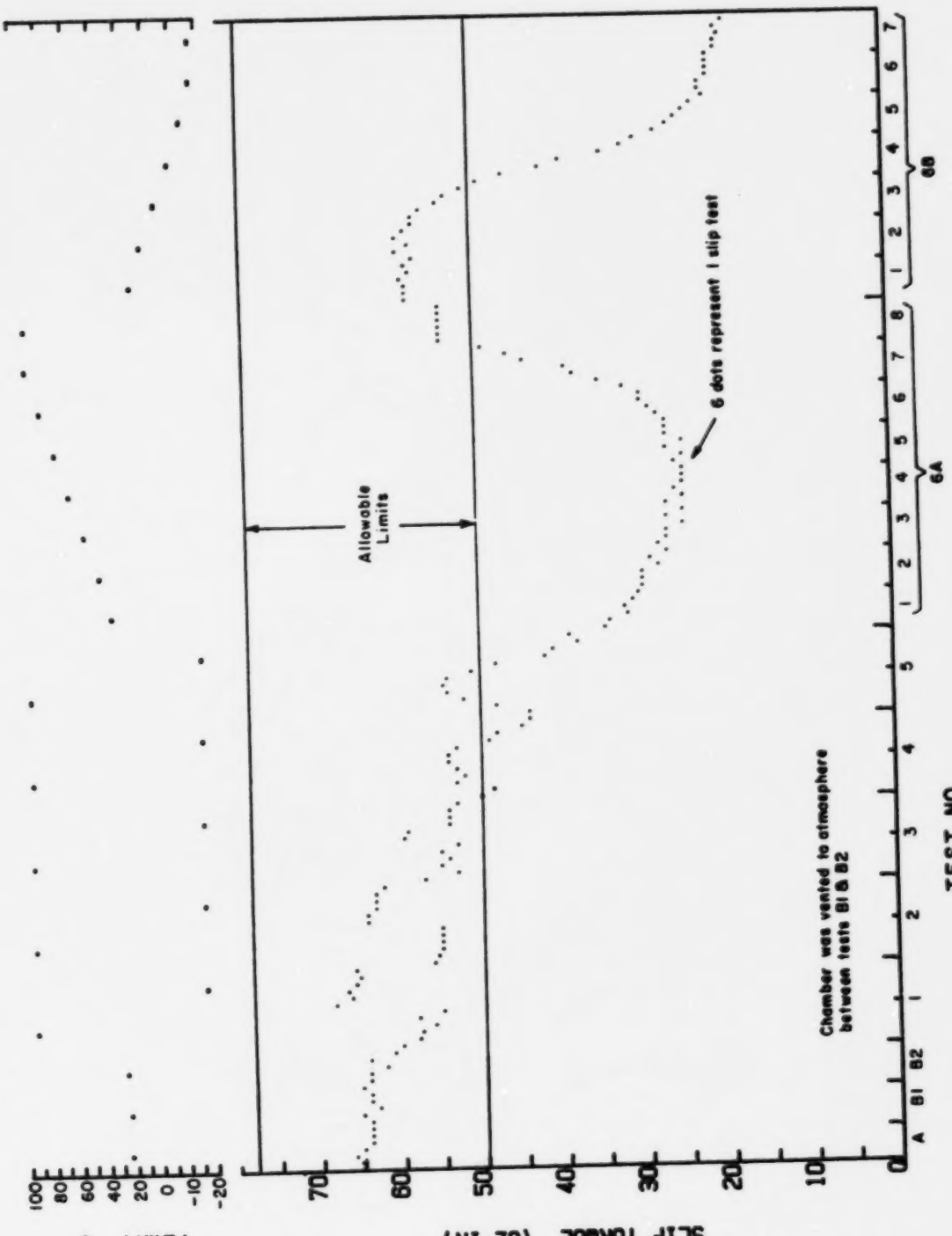


FIG. 6: SLIP TORQUE DURING NAE TESTS A TO 6B-7

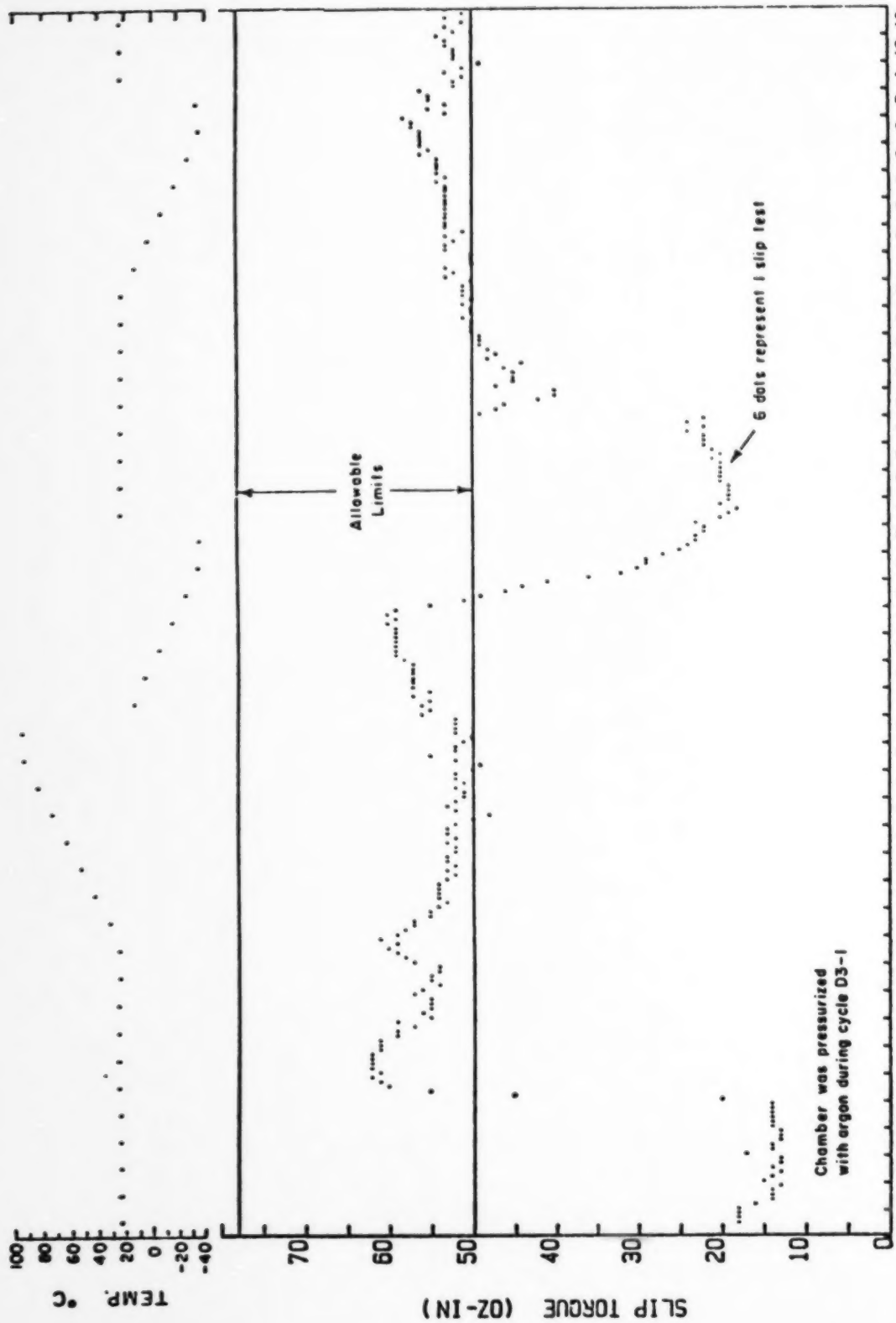


FIG. 7: SLIP TORQUE DURING NAE TESTS C1 TO I3

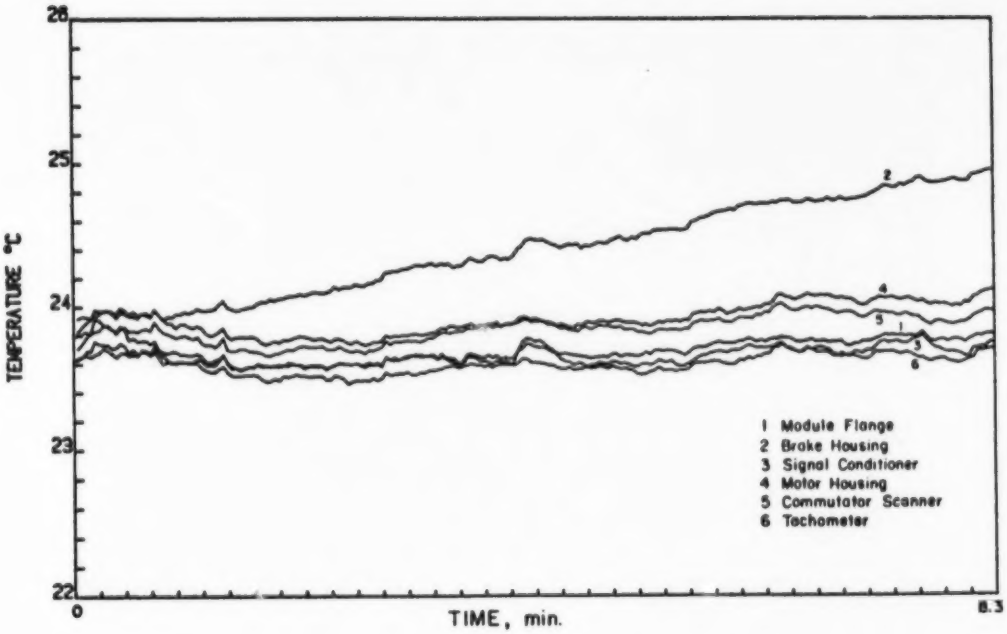


FIG. 8: MODULE COMPONENT TEMPERATURES DURING NAE TEST B1

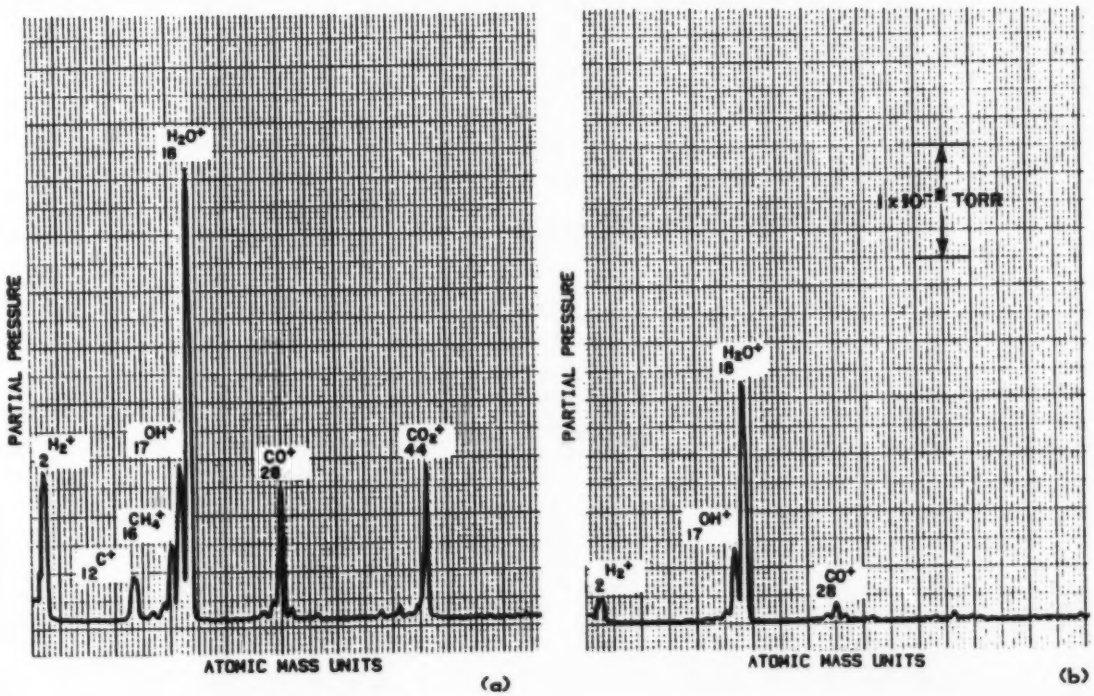


FIG. 9: MASS SPECTROMETER ANALYSES OF TEST CHAMBER ATMOSPHERE (a) DURING AND (b) AFTER BRAKE SLIP TEST

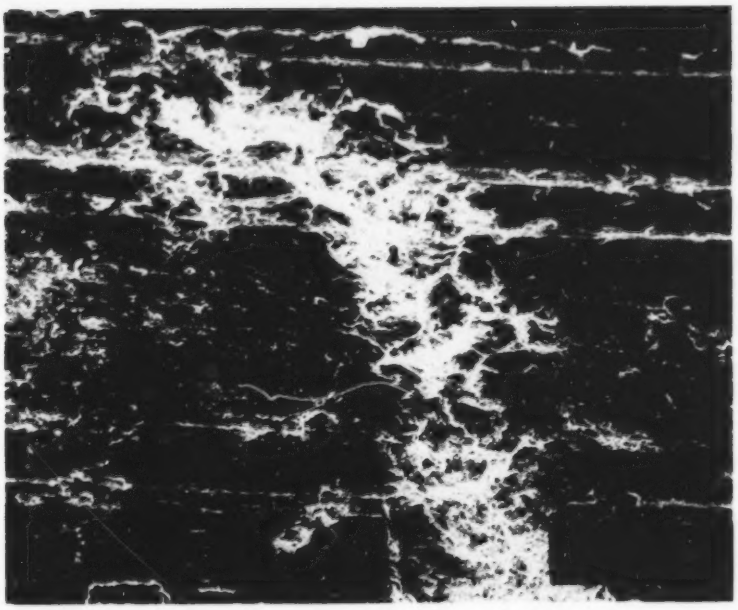
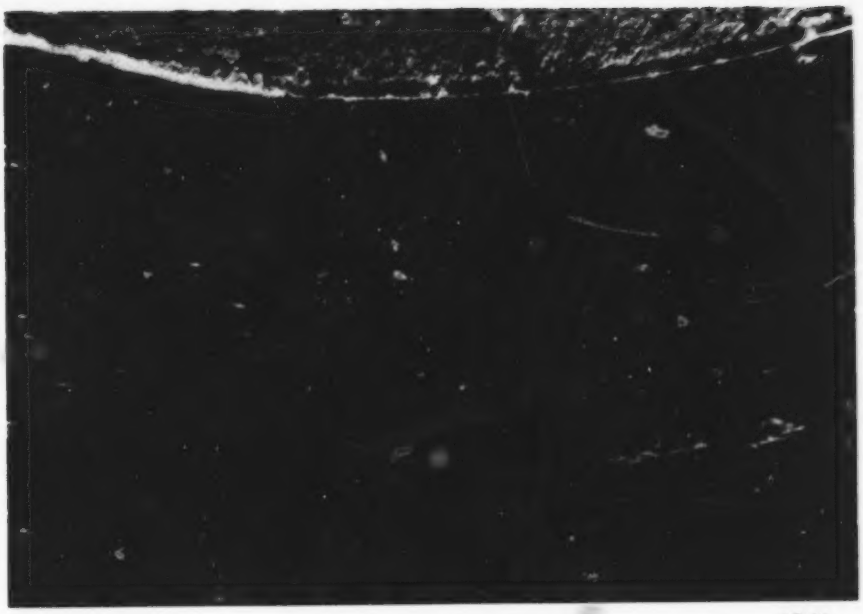
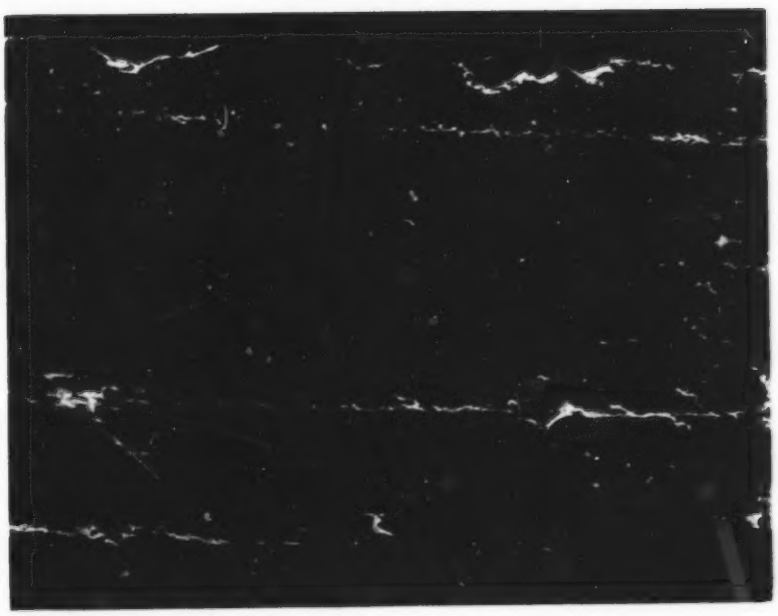


FIG. 10: BRAKE PAD SURFACE CAVITY



(a) 12 X



(b)

FIG. 11: BRAKE PAD SURFACE GROOVING

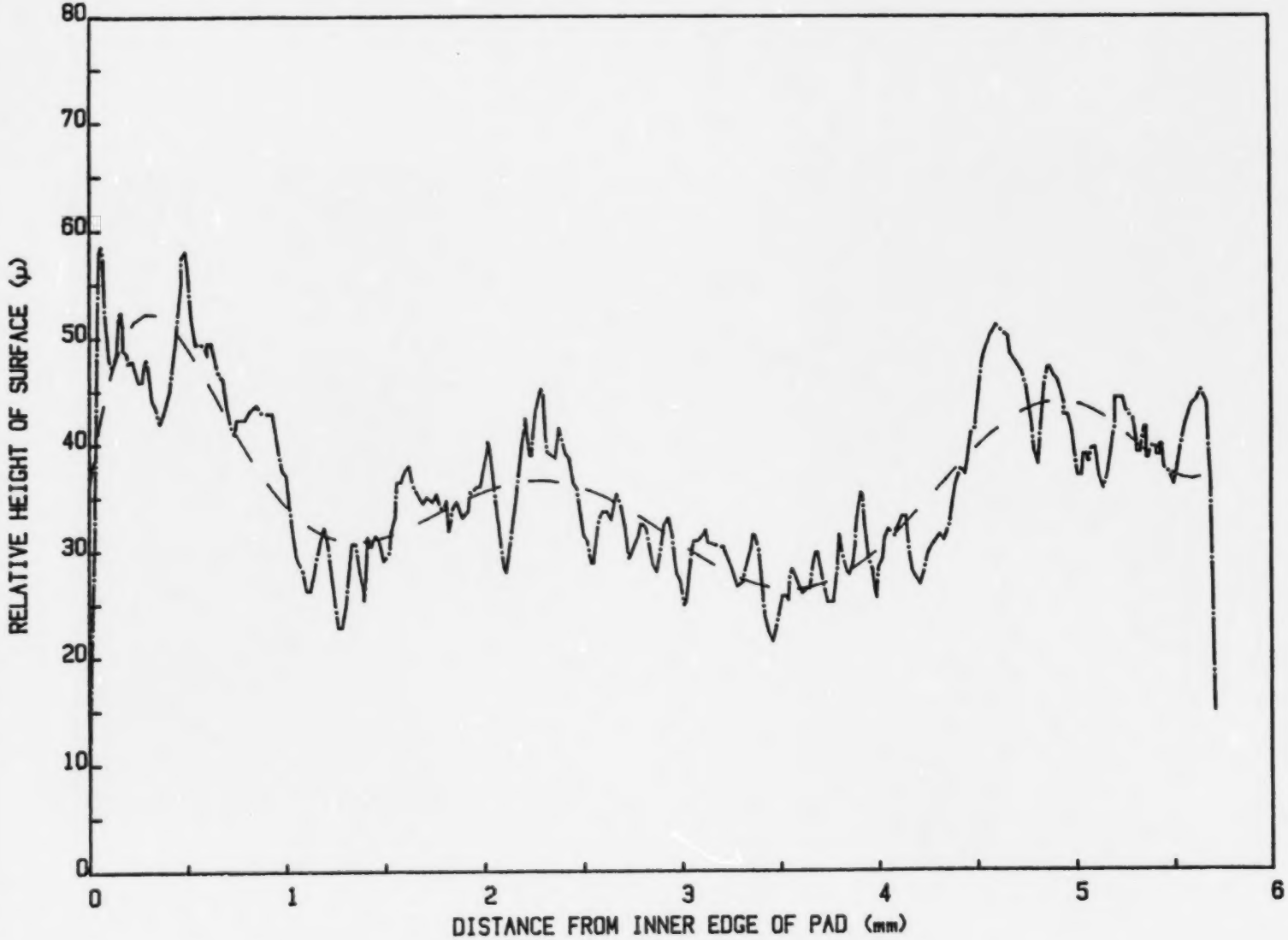


FIG. 12: SURFACE PROFILE OF ARMATURE BRAKE PAD

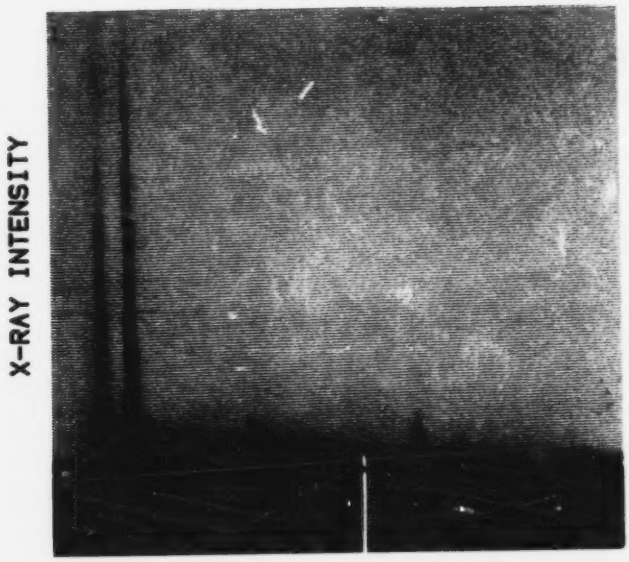


FIG. 13: XES SPECTRUM FROM ARMATURE PAD

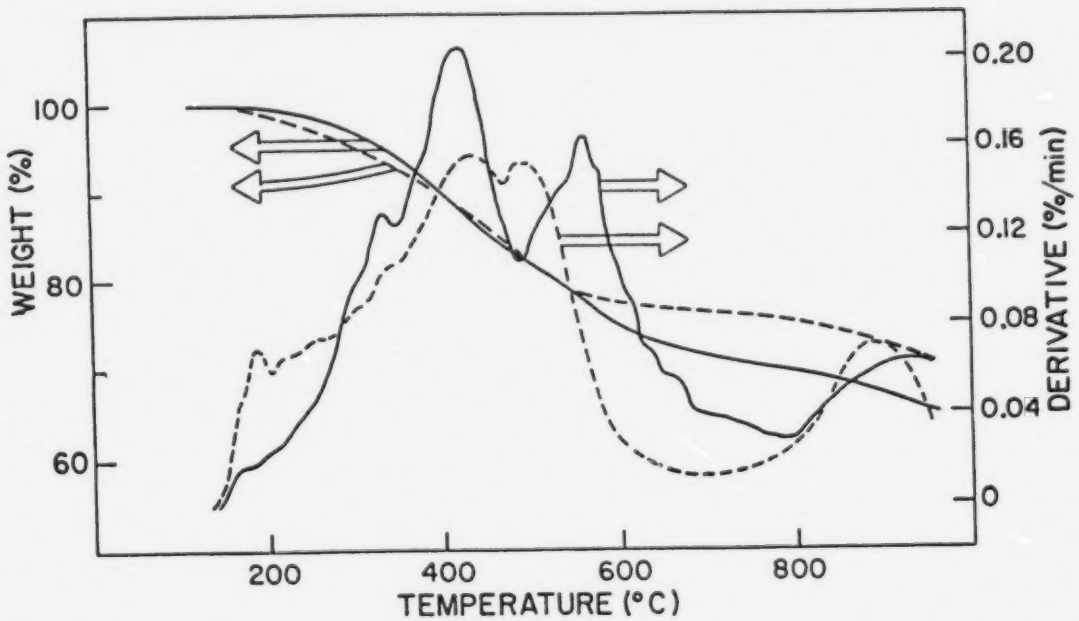


FIG. 14: TGA CURVES FOR VIRGIN FRICTION MATERIAL (—) AND BRAKE PAD WEAR DEBRIS (--) UNDER VACUUM